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Citation for published version:

Maluk, C & Bisby, L 2014, A NOVEL TEST METHOD FOR MATERIALS AND STRUCTURES IN FIRE. in *8th International Conference on Structures in Fire*. vol. 2, Tongji University Press, Shanghai, pp. 1063-1070.

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Peer reviewed version

Published In:

8th International Conference on Structures in Fire

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A NOVEL TEST METHOD FOR MATERIALS AND STRUCTURES IN FIRE

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Keywords: H-TRIS, thermal exposure, heat flux, time-temperature curve, fire resistance test.

Abstract. *A novel testing method/apparatus named the Heat-Transfer Rate Inducing System (H-TRIS) has been developed to control the time-history of incident heat flux imposed on test specimens. H-TRIS can be used to simulate a broad range of thermal exposures, from those encountered in a standard fire resistance test in a furnace to those encountered in any real (or design) fire in a real building. This is made possible by implementing a rational understanding of the fundamentals of heat transfer and a paradigm shift (from a structural fire engineering perspective) in how standard thermal exposures are prescribed; i.e. not by a single temperature in a furnace (e.g. gas temperature) but rather by a time-history of incident (or absorbed) heat flux. H-TRIS enables comprehensive experimental thermal studies with high statistical confidence and repeatability relative to furnace testing at comparatively low economic and temporal costs.*

1 INTRODUCTION

Fire safety considerations in the design of buildings' structural systems have traditionally been based on the concept of compliance, wherein the 'design' of individual structural elements is required to comply with prescribed fire safety 'acceptability' criteria defined by the regulatory authority having jurisdiction [1]. More than a century of research and development in structural fire testing has converged into widespread use of standard fire resistance tests (i.e. large scale furnace tests) as the sole means of experimentally fire rating (in the time domain of 'fire resistance') the 'performance' of a structural element exposed to a 'standard' fire (furnace time-temperature curve). The standard fire resistance test replicates only one presumed worst-case fire, despite the infinite potential fires that could occur in reality.

The current compliance testing approach results in a simplified, comparative regulatory system in which the true performance of materials and structural systems in real fires is rarely known or acknowledged. While real structures fail only rarely in fires, when they do fail it is almost always for reasons that would not be expected on the basis of standard fire resistance testing; this compellingly suggests that the complexities of real fires in real buildings are not captured in standard fire tests [2].

"Most of the existing tests had to be developed by trial and error, and they are open it is true to the objection that they do not truly indicate how a material will behave in an actual fire. They may tell us which is the better of two materials, but not whether one or both is good enough for the job." [3]

2 STANDARD FIRE RESISTANCE TEST

At the turn of the 20th Century, efforts were made both by US and European testing organizations, as well as by other stakeholders involved in the building construction community, to define a uniform 'standard' fire resistance test. As indicated in 1917 by Ira Woolson, then Chairman of the National Fire Protection Association's (NFPA) Committee on Fire-Resistive Construction, the overarching goal of

these efforts was to “unify all fire tests under one single standard and remove an immense amount of confusion within the fire testing community” [4].

2.1 Thermal exposure

Once fire testing organizations had developed standards for ‘harmonizing’ the thermal exposure (i.e. furnace time-temperature curve) to be imposed during standard fire resistance tests, the fire testing community (industry) experienced considerable growth in the number and cost of standard fire testing facilities around the world; and thus developed considerable industry inertia. Efforts aimed at further standardizing the thermal exposure experienced by tested elements during furnace tests continue to present day; for instance by seeking to regulate the materials used for furnace linings, the instruments used to control furnace temperatures, and/or the limiting gas pressure levels inside furnaces [5]. Nevertheless, current guidelines for the design and operation of fire resistance testing furnaces present relatively few requirements which aim, but which are insufficient, to truly standardize thermal exposures.

Considerable differences remain in the design, construction, and operation of fire resistance testing furnaces globally (e.g. dimensions, lining materials, positions of burner outlets, procedures to control the burner operation, fuel type, etc.) with minimal standardization schemes for both construction and operation [6]. As a result, most considerations taken into account during the design, construction and operation of a fire testing furnace are based on past experience accumulated by furnace manufacturers, rather than on a standard specification for furnace design and construction to ensure that all furnaces are as ‘equal’ as possible. This inequality between furnaces has consequences for the heat transfer to the test specimen that occurs in standard furnace tests [5]. The thermal exposure to which a structural element is exposed in a standard fire resistance test is defined in terms of a prescribed time-temperature curve. Technical and philosophical discussions on how and where temperatures (gas or otherwise) are measured and controlled in standard fire test furnaces are countless in the available literature [e.g. 7, 8, 9, 10].

While a thorough analysis of heat transfer processes in furnaces is avoided in the current paper, two noteworthy issues must be raised that are commonly misunderstood (typically by structural engineers) in regards to the definition of thermal exposure: first, that temperature variation is the result of a thermal energy exchange between a source (e.g. the ‘fire’) and a receiver (e.g. the structural element); and second, that the amount of thermal energy exchanged is directly dependent on the thermal conditions of both the *source* and the *receiver* [5]. The consequence of these realities is that it is fundamentally incorrect to control the amount of thermal energy imposed on a surface solely by controlling a single temperature (e.g. gas temperature). Two structural elements, made out of different materials but tested in the same furnace controlled to follow the same time-temperature curve are unlikely to yield a fair comparison of their performance during some presumed identical compartment fire.

“It is rather disturbing that fire resistance ratings developed for various building elements may depend to quite an extent on the laboratory conducting the tests.” [11]

The fact that that the *size* or *severity* of the fire defined in terms of a furnace time-temperature curve negates the potential for standard fire resistance tests to impose a truly standardised thermal exposure. By prescribing a single temperature (e.g. gas temperature) in the furnace, the incident heat flux imposed on a test specimen – in essence the *size of the fire* – can only be indirectly controlled [5]. Whilst the above might seem obvious to those in the fire science community, within structural fire testing it is generally accepted that controlling the time-history of temperature inside a furnace (time-temperature curve) is equivalent to controlling the thermal exposure to the element being tested. This neglects the complex thermal interactions between the specimen, gases, linings, and potential presence of luminous flames inside the furnace [5].

2.2 Mechanical loading and restraining conditions

The mechanical conditions imposed on elements tested in standard fire resistance tests, which can differ greatly from those in real building, significantly impacts upon their performance during fire.

Mechanical boundary conditions imposed during a fire resistance test may be designed to provide restraint against thermal expansion, contraction, and/or rotation, or to offer freedom of movement. Available furnaces' dimensions limit the size of the structural system (or elements) being tested, resulting in the tests being conducted on isolated elements typically smaller than 4 m in maximum dimension (with a few notable exceptions internationally). Most standard fire resistance tests are executed under 'fully fixed' or 'fully free' mechanical conditions, both being a technical challenge to achieve in practice.

"We no longer build by simply supporting beams on walls and yet we all carry out our fire tests in a way appropriate to this form of construction imposing vertical loads only." [12]

Modern testing facilities make use of highly sophisticated or overly simplified techniques for applying mechanical loading to test specimens. These include hydraulic systems, mechanically automated systems, dead weights, and others. The imposed mechanical load level applied to test specimens is defined on the basis that it should provide a reasonable representation of the mechanical conditions that would be encountered by the tested element during a fire under normal in-service conditions in a real building; this is no easy task given that thermal deformations in real structures are likely to result in time-varying mechanical loads and conditions. In recent years, considerable effort has been devoted to adapting existing testing facilities with mechanical reaction frames capable of simulating, in some cases in real-time using feedback from load and displacement sensors during the test, the mechanical actions and reactions imposed on an isolated furnace-tested element from a computationally modelled full structure [2]. Such attempts have not been particularly successful, however, therefore a gradual shift in testing philosophy to large scale nonstandard fire testing, using 'real' rather than standard fires, is underway and a number of custom made non-standard testing facilities have recently come on line or are nearing completion [2].

3 REACTING TO A NEED

The standard fire resistance test was conceived in the early 1900s mainly to standardise a field that was in need of regulation. Despite more than a century of advances (mostly technical) aimed at standardizing (and rationalizing) furnace testing procedures, numerous fundamental problems remain within structural fire testing; these include high operating costs, poor repeatability, unrealistic and/or inappropriate boundary conditions, and poor statistical confidence. Kruppa and Curtat [13] have suggested that a fundamental change is needed: *"in principle, the change in the control mode implies a change in the overall heat supply to the object tested."* During experimental research studies carried out at The University of Edinburgh on spalling of medium scale concrete specimens [5], a novel test method was conceived and developed based on the following characteristics:

- *Impose a rational, quantifiable thermal exposure* – define thermal exposure in terms of a time-history of incident heat flux, rather than a traditional time-history of temperature (e.g. furnace gas temperature) inside a furnace; hence the *"size/severity of the fire"* is directly controlled.
- *Impose a range of thermal exposures* – alongside the development of this unique testing apparatus, an inverse heat conduction model was developed to calculate the time-history of incident heat flux which yields an equivalent thermal exposure to that experienced by structural elements under potentially any heating condition (e.g. a standard fire resistance test, large scale fire test, etc.). Alternatively, a time-history of incident heat flux can be specified using outputs from a fire model (e.g. computational fluid dynamics model, zone model, etc.).
- *Repeatability* – calibration of the test method is repeated periodically (or before each new test) to account for the specific ambient conditions on any given day, allowing a very high level of repeatability between tests, thus a good statistical confidence for research studies carried out.
- *Operate at low economic and temporal cost* – experimental fire resistance research is generally limited by the high economic and temporal costs associated with performing standard fire resistance

tests, thus few (or in most cases single) tests are performed for each test variable during any particular research project. A similar scenario is experienced within compliance-driven testing schemes.

The resulting test method/apparatus, named the Heat-Transfer Rate Inducing System (H-TRIS), is the result of a mental shift associated with controlling the thermal exposure not by a single temperature but rather by the time-history of incident heat flux.

4 HEAT-TRANSFER RATE INDUCING SYSTEM (H-TRIS)

Fire test control by incident heat flux is by no means a revolutionary concept; this approach has been widely implemented by various researchers in a number of studies within the broader fire science community [e.g. 14]. Furthermore, various researchers have suggested replacing the prescribed time-history of temperature used in standard fire resistance tests with a more rational definition of thermal exposure [5].

Commercially available testing apparatuses such as the Cone Calorimeter and the FM Global (Factory Mutual Research Corporation) Fire Propagation Apparatus (FPA) are widely used to test small scale material specimens by controlling the incident heat flux imposed on a tested specimen. Arrays of fixed or mobile gas- or propane-fired radiant panels have formerly been used for testing various construction materials by controlling (or rather, imposing) a chosen incident heat flux [5]. However, in all of these prior cases the imposed time-history of incident heat flux has been calculated either based on a somewhat arbitrarily defined presumed ‘realistic’ condition, or based on a complicated heat transfer model of the conditions within a standard fire resistance testing furnace. The following sections provide a brief description of an inverse heat conduction model used to calculate the time-history of incident heat flux which yields an equivalent thermal exposure to that experienced by structural elements under potentially any heating condition, as well as the technical aspects of H-TRIS (Figure 1).

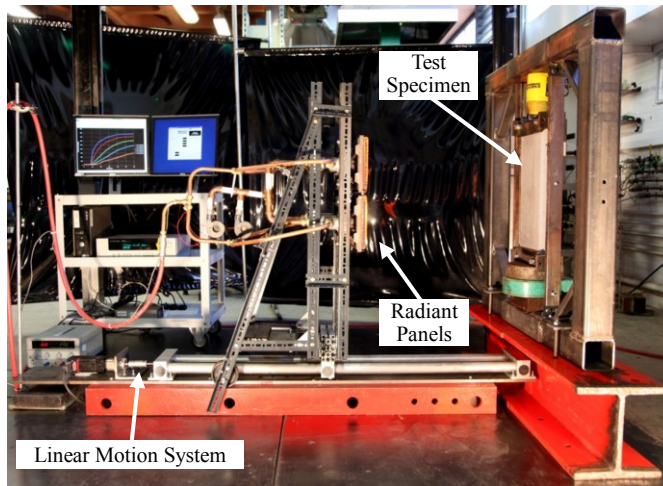


Figure 1. H-TRIS (side elevation) in its current incarnation.

4.1 Inverse heat conduction model

Calculation of transient boundary conditions for a thermodynamic system by inverse modelling is frequently performed for a number of applications in various different fields of study [5]. In its most rudimentary form, an inverse heat conduction model calculates the time-history of a thermal boundary condition based on through-thickness temperature measurements taken within a body during heating. The

particular model applied herein calculates the time-history of incident heat flux (imposed with H-TRIS on the target exposed surface of the test specimen) that yields an equivalent time-history of through-thickness temperatures for identical specimens exposed to heating in a standard fire resistance test. The procedure can potentially be used to calculate the time-history of incident heat flux which yields any time-history of through-thickness temperatures for any source of heating on essentially any material with reasonably well characterized thermal properties [5].

Calculations of incident heat flux are made by considering the particular thermal conditions encountered when testing a specimen with H-TRIS at the exposed and unexposed surface of the test specimens. The time-history of incident heat flux at the target exposed surface is calculated as:

$$\varepsilon \cdot \dot{q}_{inc}'' = \dot{q}_{abs}'' + \dot{q}_{rad}'' + \dot{q}_{conv}'' \quad (1)$$

Where \dot{q}_{abs}'' is the time-history of absorbed heat flux which yields the time-history of through-thickness temperatures for identical specimens exposed to heating in a standard fire resistance test (or other source of heat), and \dot{q}_{rad}'' and \dot{q}_{conv}'' are the losses due to radiation and convection at the exposed surface, respectively. Convective losses are determined using an empirical correlation for free convection from a heated surface. Figure 2 presents the results (outputs in terms of the calculated absorbed heat flux based on through thickness temperature measurements in the materials) of an inverse model carried out for steel, concrete and Aircrete® test specimens during a furnace test. Aircrete® is a lightweight material made from pulverised fuel ash (80%), which presents similar thermal properties to those of a furnace's linings. Figure 2 demonstrates a potentially important material dependency of thermal exposure in fire testing; i.e. different materials tested under the same time-temperature curve do not experience the same time-history of absorbed (nor incident) heat flux. This confirms that the idea of a prescribed time-temperature curve for fire testing of different materials is fundamentally flawed. A thorough experimental validation of H-TRIS' ability to replicate the through-thickness temperature of various test specimens and various materials during a furnace test has previously been performed and is presented elsewhere [5].

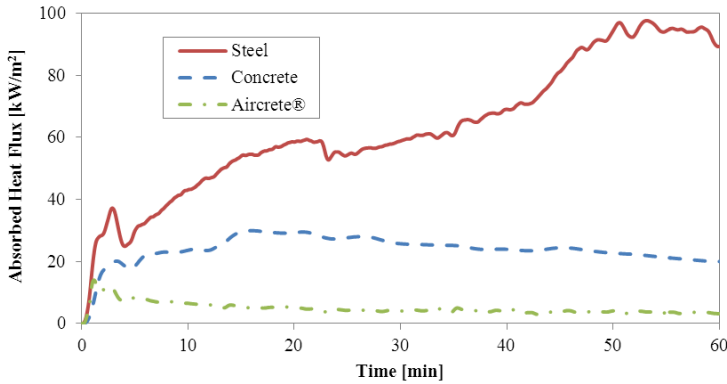


Figure 2. Calculated absorbed heat flux experienced by a range of materials during a standard fire resistance test, calculated using an inverse heat conduction model.

4.2 Technical aspects of H-TRIS

Practically speaking, H-TRIS uses a mobile array of propane-fired radiant panels along with a mechanical linear motion system (see Figure 1). The radiant panels' position is actively controlled to uniformly expose a target exposed surface ($200 \times 400 \text{ mm}^2$ in the tests described herein) on test specimens to a predefined time-history of incident heat flux [5]. This allows for minimum (farthest position to the target exposed surface) and maximum (closest position to the target exposed surface) incident heat fluxes of about 3 and 100 kW/m^2 , respectively. Work is currently underway to develop a new version of H-TRIS, which will be capable of achieving multiple and larger exposed surfaces, as well

a higher maximum incident heat fluxes sufficient to simulate hydrocarbon and tunnel fire exposures [15]. Additionally, H-TRIS is complemented with a purpose built structural loading frame designed to apply constant or variable axial compressive loads on test specimens during heating. In its current incarnation, specimens can be loaded in axial or bi-axial compression whilst being exposed to heating; up to a maximum capacity in each axis of 150 kN.

5 RESEARCH STUDIES

To date, numerous research-driven as well as product development projects have been executed or are scheduled with H-TRIS; these have tested a broad range of building construction materials (e.g. concrete, intumescent fire protection coatings, plaster and magnesium oxide board, glass wall panels, and cross-laminated timber panels). A brief description of some of these exemplar projects is given in the following sections.

5.1 Concrete

Although compliant with available testing standards, a study performed by the authors [5] showed that non-homogeneity of the temperature distribution inside a furnace (5 to 10% deviation during the first 30 minutes of the test), appeared to have an important influence on the occurrence of heat-induced concrete spalling of large scale prestressed high-performance self-consolidating concrete (HPSCC) slabs tested simultaneously during a single standard fire resistance test. Fair comparison of spalling test results is therefore questionable if thermal exposure variability is not considered. Consequently, neither a rational understanding of heat-induced concrete spalling nor an ability to prevent it during real fires is likely to be achieved only by performing additional standard fire resistance tests in furnaces.

A comprehensive yet practical experimental study of heat-induced concrete spalling was carried out using H-TRIS, with emphasis on studying the use of polypropylene (PP) fibres of various types, sizes, shapes, and dosages to mitigate heat-induced concrete spalling. Eleven different high-performance, high-strength, self-compacting concrete (HPSCC) mixtures were evaluated (see Figure 3).

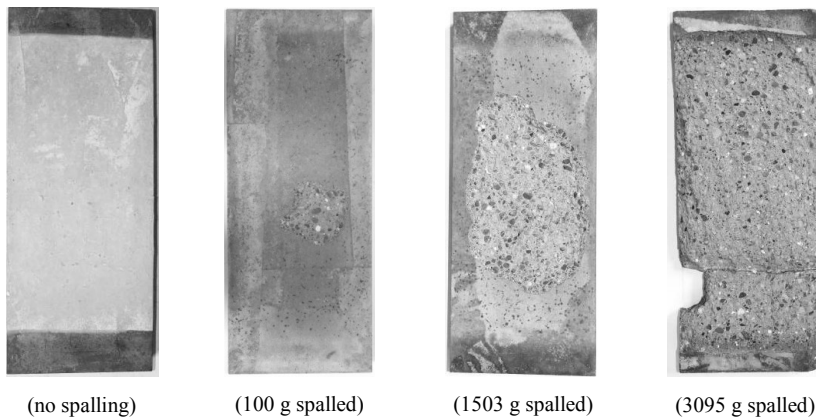


Figure 3. Post-test photographs of concrete specimens tested with H-TRIS [5]. Various severities of spalling observed for various concrete mixes and PP fibre doses.

H-TRIS allowed parameters and conditions that are known to promote (or avoid) the occurrence of spalling to be repeatable and inexpensively investigated. Unlike traditional furnace tests, tests carried out with H-TRIS enabled precise quantification of the time to first spalling, the mass of concrete spalled (see Figure 3), and the accumulated ‘absorbed heat density’ (i.e. the area under the time-absorbed heat flux curve) of the tested specimens. This last parameter could potentially allow for rational comparison

between specimens tested under various thermal exposures (i.e. tested under different time-histories of incident heat flux). The occurrence of heat-induced concrete spalling for specimens tested with H-TRIS was in good agreement (in terms of time-to-spalling) with identical concrete specimens tested during a set of full scale fire resistance tests previously performed by the authors [16]. All tests in this study (>80 tests in total) were performed during a total period of only 30 days, demonstrating the low temporal costs involved in using H-TRIS for simulating thermal exposures of concrete specimens during furnace tests; this would likely have taken a year or more in a standard fire testing furnace.

5.2 Intumescent coatings

Results from an experimental study on intumescent (reactive) coatings using H-TRIS allowed examination of the effective variable thermal conductivity (the basis for the design of protected structural steel in fire) of a commercially available intumescent coating when subjected to various time-histories of incident heat flux. Test results showed that the heating rate and thickness of the coating do not drastically affect the development of the coating's effective thermal conductivity, leading to a proposal for a simplified method for experimentally characterizing and specifying coating requirements and/or for performing heat transfer design calculations when designing to protected structural steel elements in non-standard heating regimes [17]. Such variable thermal conductivities are essential for rational performance-based structural fire safety design of intumescent protected steel framed buildings.

5.3 Timber

The behaviour of glued, nailed, and dowel laminated timber has been experimentally evaluated by testing medium scale timber panel specimens with H-TRIS; in this case programed to replicate the thermal exposure experienced by equivalent timber specimens during a standard fire resistance test in a fire resistance testing furnace. Three time-temperature curves were evaluated in this study: standard cellulosic, smouldering, and hydrocarbon [15] in addition to a number of ad-hoc time varying incident heat flux scenarios intended to replicate thermal exposure arising from rationally defined t-squared design fires. This study has demonstrated that once established, the Eurocode [18] timber charring rate of 0.65mm/min is broadly correct for the various different heat flux curves, however the initiation of charring may vary and in some cases the charring rate may be unconservative. The charring rate dependency on thermal exposure is indispensable to apply alternative design fire scenarios, particularly travelling fire scenarios [19], in the rational performance-based structural fire safety design of cross laminated timber (CLT) buildings.

6 CONCLUSIONS

The standard fire resistance furnace test has traditionally been used for assuring regulatory compliance of structural elements and assemblies, and in countless cases also for scientific understanding of experimental structural response to fire. As the fire engineering community drives towards the acceptance and implementation of performance based structural fire engineering designs [5], it is fundamentally incorrect to depend entirely on conventional fire testing and rating (or equivalent) of structural and non-structural systems as the sole motivation (and experimental tool) for product manufacturers, designers, regulators and researchers.

H-TRIS is an experimental tool that allows researchers to conduct studies with high repeatability and quantifiable (and rational) thermal boundary conditions, all at low economic and temporal cost. This will potentially allow for the execution of comprehensive experimental studies with high statistical confidence relative to furnace testing. H-TRIS can be used to replicate a broad range of thermal exposures, from those encountered in a standard fire resistance test to those encountered in any 'real' design fire.

It is hoped that forthcoming research projects and developments around H-TRIS will promote an industry-wide move away from the modern pass/fail large scale furnace testing environment, characterized by its high operating costs, poor repeatability, unrealistic and/or inappropriate boundary conditions, and poor statistical confidence.

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